DOWNHOLE TEMPERATURE PREDICTION FOR DRILLING GEOTHERMAL WELLS

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ABSTRACT

Unusually high temperatures are encountered during drilling of a geothermal well. These temperatures affect every aspect of drilling, from drilling fluid properties to cement formulations. Clearly, good estimates of downhole temperatures during drilling would be helpful in preparing geothermal well completion designs, well drilling plans, drilling fluid requirements, and cement formulations.

The thermal simulations in this report were conducted using GEOTEMP, a computer code developed under Sandia National Laboratories contract and available through Sandia. Input variables such as drilling fluid inlet temperatures and circulation rates, rates of penetration, and shut-in intervals were obtained from the Imperial Valley East Mesa Field and the Los Alamos Hot Dry Rock Project.

The results of several thermal simulations are presented, with discussion of their impact on drilling fluids, cements, casing design, and drilling practices.

DISCLAIMER

1. Introduction

Drilling geothermal wells can be more difficult than drilling oil wells because of the unusually high temperatures encountered (as well as other problems such as lost circulation [1]). High wellbore temperatures strongly effect the performance of drilling fluids, cements, well casing and tubing, and the elastomers and seals in packers.

Determination of downhole wellbore and earth temperatures is a complex task. Many variables influence temperatures, which are continuously changing with time. Temperature recording devices have been developed, but these provide only isolated data points for a transient quantity and, furthermore, cannot provide sufficient information to establish the relative importance of variables influencing temperatures. Therefore, a means of computing downhole temperatures is needed to determine important design criteria, such as maximum temperature and time for exposure to high temperatures. Experience has demonstrated that a computer model is needed to account for complexities of heat transfer in a well.

Because of this need, Sandia Laboratories has funded the development of a wellbore thermal simulator called GEOTEMP by Enertech Engineering and Research Co. Currently a second project to enhance the capabilities of GEOTEMP is being conducted. The simulations presented in this paper were conducted with this advanced form of GEOTEMP. This advanced GEOTEMP code will be available from Sandia in Spring of 1981.

Two drilling simulations were conducted, the first based on the GT-2 well drilled in the Los Alamos Hot Dry Rock Project and the second based on geothermal well #56-30 drilled by Republic Geothermal in the Imperial Valley East Mesa Field. The drilling fluids, circulation rates, drilling rates, and shut-in periods that were used in the actual wells were modeled by the thermal simulator. The thermal predictions from these studies are used to discuss:

1. Wellbore temperatures during drilling as a function of depth,

2. Bit temperatures over the drilling history,

3. Cement temperatures from setting to the end of drilling, and

4. Casing temperatures at selected depths over the drilling history.

2. The GEOTEMP Simulator

The major technical features of GEOTEMP are summarized in the following:

1. The flowing stream energy balance is a fully transient analysis with vertical heat convection, and radial heat conduction. Such a fully transient behavior has not previously been available for public use.

2. A composite of annular materials makes up the wellbore description, including the steel, cement, and fluids present in a well. A fully transient radial heat conduction model accounts for the wellbore region. Material heat capacities and natural convection in annular fluids are both included.

3. Radial and vertical heat conduction are the bases for the transient energy transfer in the soil. A key feature in the thermal simulator is the direct coupling of soil and well temperature calculations.

Particular emphasis has been placed on highly transient short time intervals, complex flow histories such as occur in drilling, and flexibility to allow sequential combinations of all flowing possibilities. With the code described in this paper, the complete life of a well can be modeled with one computer run for drilling and circulation during completion, through production and circulation during workover, additional production or injection through the life of a well, and even shut-in after a well is dead.

The original GEOTEMP was developed with only a single primary flowing fluid. The modified GEOTEMP currently under development allows several different wellbore fluids to be defined, and allows the user to specify the injection, production or circulation of any fluid at any time in the life of the well. Further, more than one fluid may be in the wellbore at any time, and the displacement of one fluid by another is automatically computed. The simulation of a cementing operation is one application of this capability.

The original GEOTEMP was developed to model liquid wellbore systems. The modified GEOTEMP now has the capability of simulating air and nitrogen drilling. The simulation can switch between air drilling and mud drilling at any time desired.

The GEOTEMP thermal simulator has been thoroughly tested against analytic solutions to several heat transfer problems and been shown to be very accurate. Field data was acquired from geothermal and petroleum wells for flowing and shut-in conditions to correlate with GEOTEMP. The performance of the thermal simulator in modeling this field data was excellent [2].

3. Geothermal Well Simulations

The GEOTEMP simulator was designed to allow the thermal simulation of the complex drilling and completion process of a typical geothermal well. Table 1 summarizes the drilling history of the Los Alamos GT-2 well. Twenty two separate time periods, six different drilling fluids, varied flow rates, and continuously changing depths characterize the drilling of this well. Table 2 summarizes the drilling history of Republic Geothermal well #56-30. Though not as complex as the Los Alamos well, a thermal simulation of this well would still require four different wellbore fluids, four different flow rates, and varying depth.

Tables 3 and 4 give the well completions of the Los Alamos and Republic wells, respectively. The Los Alamos well is completed with three different size casings and a drill pipe is specified. The Republic well is completed with four different casings and a drill pipe size is specified here also.

The input for the GEOTEMP thermal simulator is sufficiently flexible to completely specify the drilling histories and well completions of Tables 1-4. The remainder of this discussion will focus on particular results from these two thermal simulations.

A. Wellbore Temperatures

Figures 1-4 show the variation of wellbore temperatures with depth in the Los Alamos well at two selected time periods. Figure 1 shows the temperatures at the end of drilling on day 77, Figure 2 shows the temperatures at the end of the shut-in period of day 77. This drilling/shut-in pattern is repeated for the Los Alamos well in Figure 3 and 4 and for the Republic well in Figures 5 and 6. In Figures 1-6 the lines with circles give the tubing temperatures, the lines with squares give the annulus temperatures, and the unmarked lines gives the undisturbed geothermal temperature.

The key to the understanding of Figures 1-6 is the concept of the wellbore as a cross-flow heat exchanger. In Figures 1, 3 and 5 the annulus temperature exceeds the tubing temperature. Thus, the tubing fluid is heated as it flows down the drill pipe and its temperature increases continuously. The temperature of the annulus fluid is more difficult to predict because, while the annulus fluid is being cooled by the tubing fluid, it may be either heated or cooled by the surrounding soil, depending on depth. The balance between the cooling effect of the tubing fluid and the heating effect of the formation determines if the annulus fluid heats up or cools off. Of course, above the depth where the annulus temperature exceeds the geothermal temperature, the annulus temperature always decreases. Figure 1 shows the formation to be dominant in the annulus heat transfer. Note that the annulus temperature continues to increase until it crosses the geothermal line. In Figure 3, the tubing fluid has more influence, and the annulus temperature starts to decrease before the geothermal line is crossed. Figure 5 shows a dominant effect by the tubing, thus the annulus fluid cools continuously.

Mass flow rate is the governing factor in the differences among Figures 1,3, and 5. Figure 1 represents an air drilling simulation with a relatively low mass flow rate. The formation temperature governs the annulus heat transfer and there is a relatively large temperature difference between the annulus and tubing temperatures. Figure 5 results from the high mass flow rate of a conventional mud drilling. The annulus and tubing temperatures are nearly the same and the formation temperature has less relative effect on the fluid heat transfer. Figure 3 represents an intermediate case.

Figures 2,4, and 6 show the effect of shut-in on the wellbore temperatures. In each case, the temperatures move toward the undisturbed geothermal temperatures. In Figure 2, the tubing temperature has lagged 15°-20° behind the annulus temperature, and this indicates the reduced ability of air to transfer heat compared to liquid systems. In Figures 4 and 6, the tubing and annulus temperatures in the liquid wellbore fluids are within a couple of degrees of each other. While the temperatures in all cases have not reached the geothermal temperature, it will be shown in Figures 9 and 10 that the wellbore temperatures have reached the temperature of the formation immediately in contact with the well. The conclusion is that a typical shut-in period is long enough for the wellbore fluid to reach equilibrium with the formation, but not long enough for the formation to return to its undisturbed temperature.

B. Bit Temperatures

Figures 7 and 8 give the temperatures at the drill bit over the drilling history of the Los Alamos and Republic wells respectively. Also indicated on the figures are the inlet temperatures, marked with circles, and the geothermal temperatures, marked with a solid line. These two curves represent extreme temperatures for the bit, and Figures 7 and 8 show that the bit temperature stays between them over the drilling history. The Los Alamos well is the most interesting because of the variety of drilling fluids and circulation rates used.

One notable result is that foam and air drilling are not as effective as conventional drilling fluids. Air and foam drilling are indicated on Figure 7, and in each case the bit temperature shows a significant increase over drilling with liquid systems. A temperature increase late in the drilling history indicates a reduction in daily circulation time from 18 to three hours. An increase to five hours of circulation per day reduced the bit temperature by 40° to 50°.

Figure 8, though not as dramatic as the Los Alamos simulation, clearly shows the effect of time on the bottom hole temperature in the Republic well. At the eighth day and the twenty fourth, the daily hours of circulation were reduced because of logging operations, and in each case the bottom hole temperature increased, compared to bottom hole temperatures during drilling.

C. Cementing Temperatures

Figures 9 and 10 show a possible application of GEOTEMP to cementing operations. Figure 9 shows the radial temperature distribution at the end of cementing (square symbols) and at the end of "waiting on cement" time for the Los Alamos well. The solid line represents the initial undisturbed geothermal temperature. Figure 10 shows a similar plot for the Republic well. In each case, the cement is initially at a temperature 70° to 80° below the formation temperature. This formation temperature has been cooled by drilling operations by 20° in the Los Alamos well and 10° in the Republic well. At the end of the waiting period, the cement temperature has risen to the formation temperature, but it is still cooler than the initial undisturbed temperature.

The possible application of GEOTEMP would be to help design a cementing program where high formation temperatures make cement selection difficult and expensive. The simulations shown in Figures 9 and 10 indicate that the formation temperature governs the cement temperature but also that previous drilling operations have reduced the formation temperature. GEOTEMP could be used to design a circulation program to cool the formation sufficiently to help the cement operation.

D. Casing Temperatures

The final four figures relate temperature predictions to casing design. Figures 11 and 12 show the temperature of the 13-3/8" surface casing used in the Los Alamos well at two different depths over the drilling history of the well. Figures 13 and 14 show the same results for the Republic well. In each figure, square symbols indicate maximum temperatures, circles indicate minimum temperatures, and the solid line shows the undisturbed temperature as reference.

The temperature variation of about 60°F indicated at the casing seat of the Los Alamos well (Figure 11) corresponds to thermal stress changes of about 10,000 psi. The temperature changes at 400 ft range about 20°F, corresponding to 3,500 psi stress changes. These stress changes are large enough that they need to be considered in teh well completion design [3]. Figures 13 and 14 indicate a temperature range of about 30°F at the surface casing seat the temperatures are uniformly below the disturbed temperature and at 400 ft the temperatures are above the geothermal temperature. Thus, at shut-in, the casing at 1400 ft will experience compressive thermal stress and the casing at 400 ft will feel tensile thermal stresses.

A useful application of GEOTEMP would be to simulate casing temperatures through drilling and the production life of a geothermal well. The resulting estimates of thermal stresses could be used to design the well completion. In difficult design cases, safety factors could be relaxed somewhat, because of the better thermal stress estimates.

4. Conclusion

The planning of a geothermal well can be aided by good estimates of wellbore and formation temperatures during drilling. Wellbore and bit temperatures are needed to help select drilling fluids. Knowledge of temperatures during cementing help the selection of cost effective cement formations and help design the cementing operations. Casing temperatures during drilling and production are needed to estimate thermal stresses for well completion design.

The GEOTEMP wellbore thermal simulator has been designed to provide this inforamtion. The actual well completion can be completely designated and all drilling parameters, such as drilling fluids, inlet temperature, flow rate, penetration rate, and hours of drilling per day, can be specified and changed at any time in the drilling history. Full information about wellbore and formation temperatures is provided at user selected times.

Four applications of the GEOTEMP simulator, 1. wellbore temperatures, 2. bit temperatures, 3. cementing temperatures, and 4. casing temperatures have been demonstrated. The drilling simulations were based on two actual geothermal well drilling histories, the Los Alamos GT-2 well and the Republic Geothermal #56-30 well.

REFERENCES

[1]Malcolm A. Goodman, "Lost Circulation Experience in Geothermal Wells", presented at the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

[2]Gary R. Wooley, "Computing Downhole Temperatures in Circulation, Injection, and Production Wells", Journal of Petroleum Technology, September 1980.

[3]Carl Gatlin, Petroleum Engineering, Drilling And Well Completion, Prentice-Hall, Englewood Cliffs, N.J., 1960.

TABLE 1 LOS ALAMOS GT-2 WELL

DRILLING HISTORY

Time (Days)	Depth (Ft)	Circ. Rate	Hrs. Circ Per Day	Fluid*
0	0	125 gal/min	8.0	2
11.0	1595	125 gal/min	8.0	1
25.0	1595	125 gal/min	3.0	4
27.0	1595	300 SCF/min	8.0	Foam
48.0	2514	125 gal/min	3.0	4
50 0	2514	1245 SCF/min	11.0	Air
65.0	3556	1270 SCF/min	6.0	Air
78.0	3556	125 gal/min	5.0	1
87.0	3727	1275 SCF/min	3.0	Air
91.0	3727	125 gal/min	3.0	1
101.0	3727	1290 SCF/min	14.0	Air
105.0	3963	125 gal/min	15.0	1
114.0	4556	125 gal/min	11.0	3
148.0	6356	125 gal/min	0.0	1
194.0	6356	125 gal/min	13.0	1
199.0	6700	125 gal/min	5.0	1
236.0	6700	125 gal/min	15.0	1
258.0	8577	125 gal/min	1.0	1
263.0	8577	125 gal/min	18.0	1
268.0	9436	125 gal/min	3.0	1
276.0	9549	125 gal/min	5.0	1
292.0	9549	125 gal/min	5.0	1
295.0	9610	125 gal/min	5.0	1

*Fluid	Density (Lb/Gal)	Plastic Visc. (Centipoise)	Yield Point (Lb/100 Ft^2)
1	8.3	1.0	0.0
2	9.3	10.0	3.0
3	8.6	5.0	2.0
4	15.1	30.0	50.0

TABLE 2 REPUBLIC 56-30 WELL

DRILLING HISTORY

Time (Days)	Depth (Ft.)	Circ. Rate	Hrs. Circ. Per Day	Fluid*
0	0	480 gal/min	17.0	1
1	1513	480 gal/min	5.0	1
2	1513	500 gal/min	20.0	2
10	5330	360 gal/min	2.0	3
17	5330	360 gal/min	17.0	4
24	7520	400 gal/min	2.0	4

* Fluid	Density (Lb/Gal)	Plastic Visc. (Centipoise)	Yield Point (Lb/100 Ft^2)
1	8.8	4.0	4.0
2	9.0	7.0	4.0
3	8.9	22.0	17.0
4	8.9	9.0	5.0

TABLE 3 LOS ALAMOS GT-2 WELL COMPLETION

Use	Size	Weight/Ft.	Setting Depth
Conductor Pipe	20"	94.0	80.
Surface Casing	13-3/8"	48.0	1600.
Production Casing	10-3/4"	45.5	2535.
Drill Pipe	5-1/2"	21.9	N.A.

TABLE 4 REPUBLIC 56-30 WELL COMPLETION

Use	Size	Weight/Ft.	Setting Depth
Conductor Pipe	20"	94.0	90.
Surface Casing	13-3/8"	54.5	1503.
Protective Casing	8-5/8"	32.0	5320.
Production Casing	6-5/8"	28.0	7520.
Drill Pipe	3-1/2"	9.5	N.A.

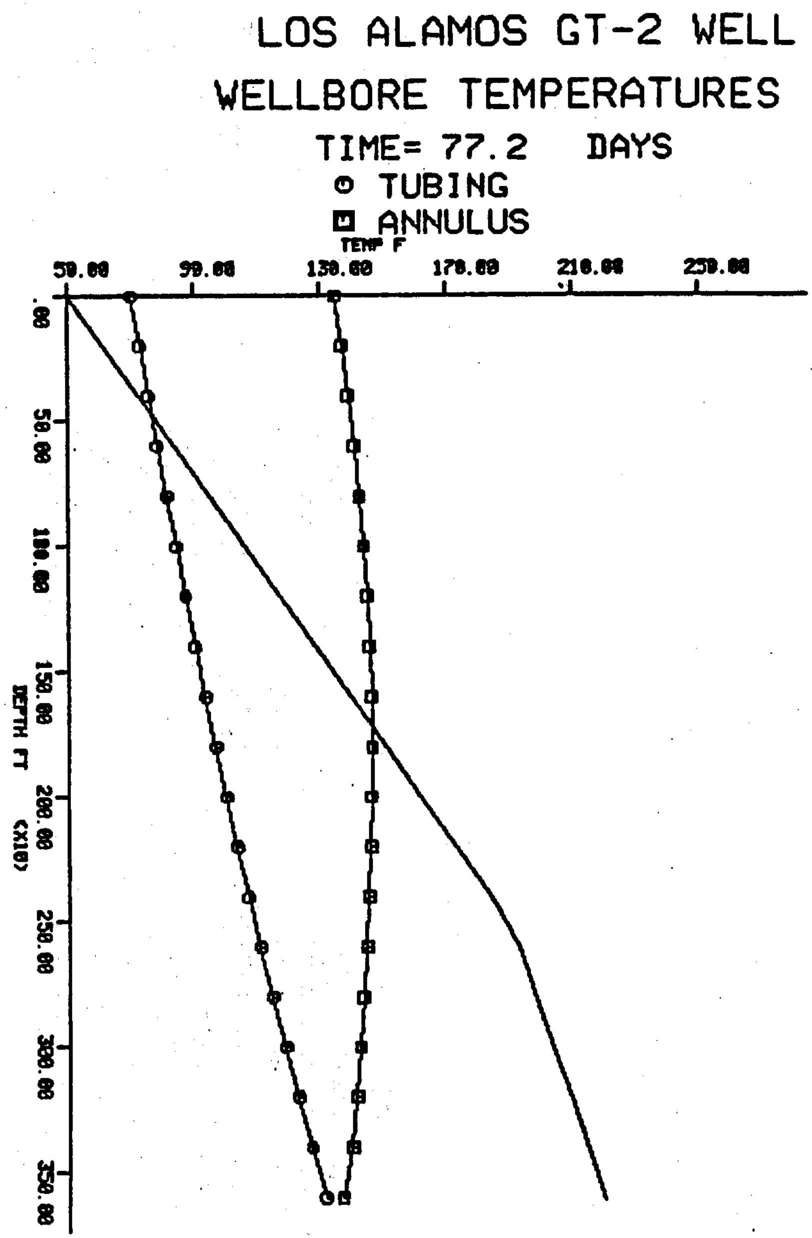

FIGURE 1

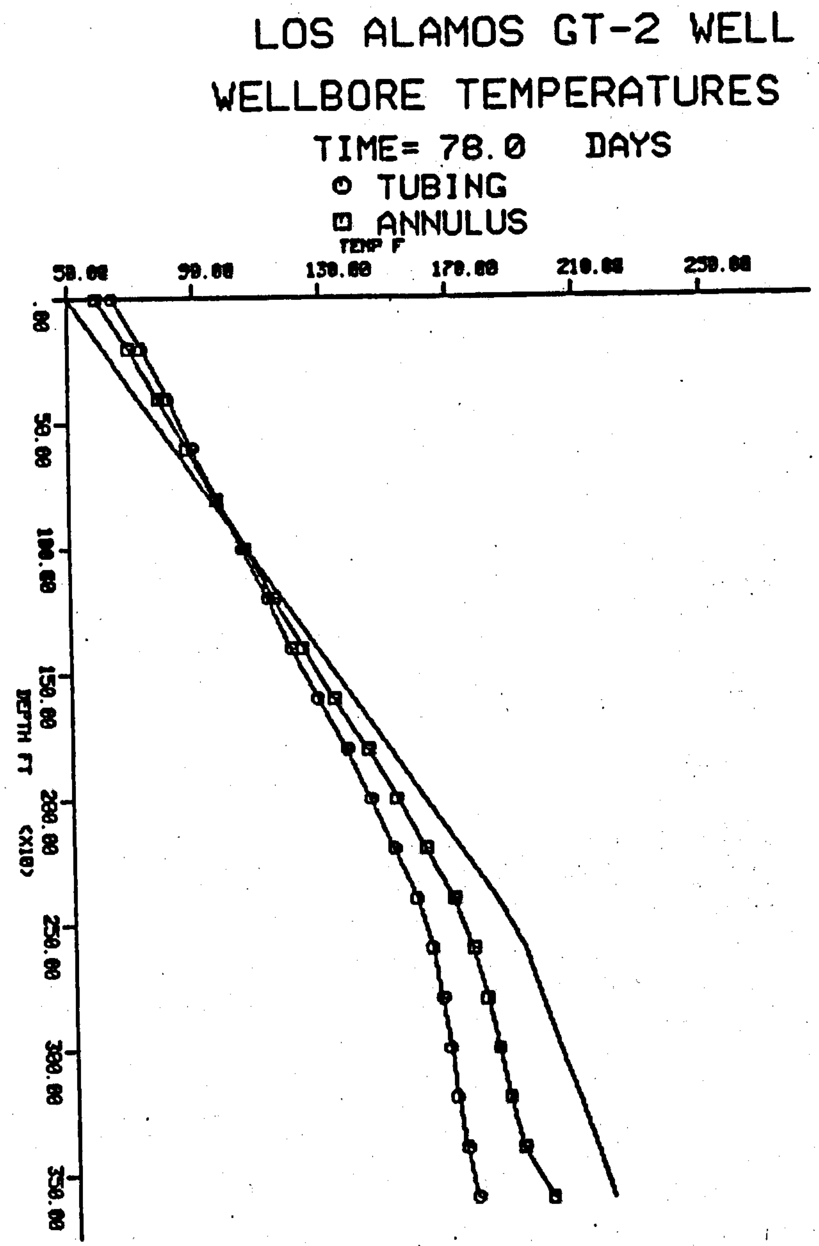

FIGURE 2

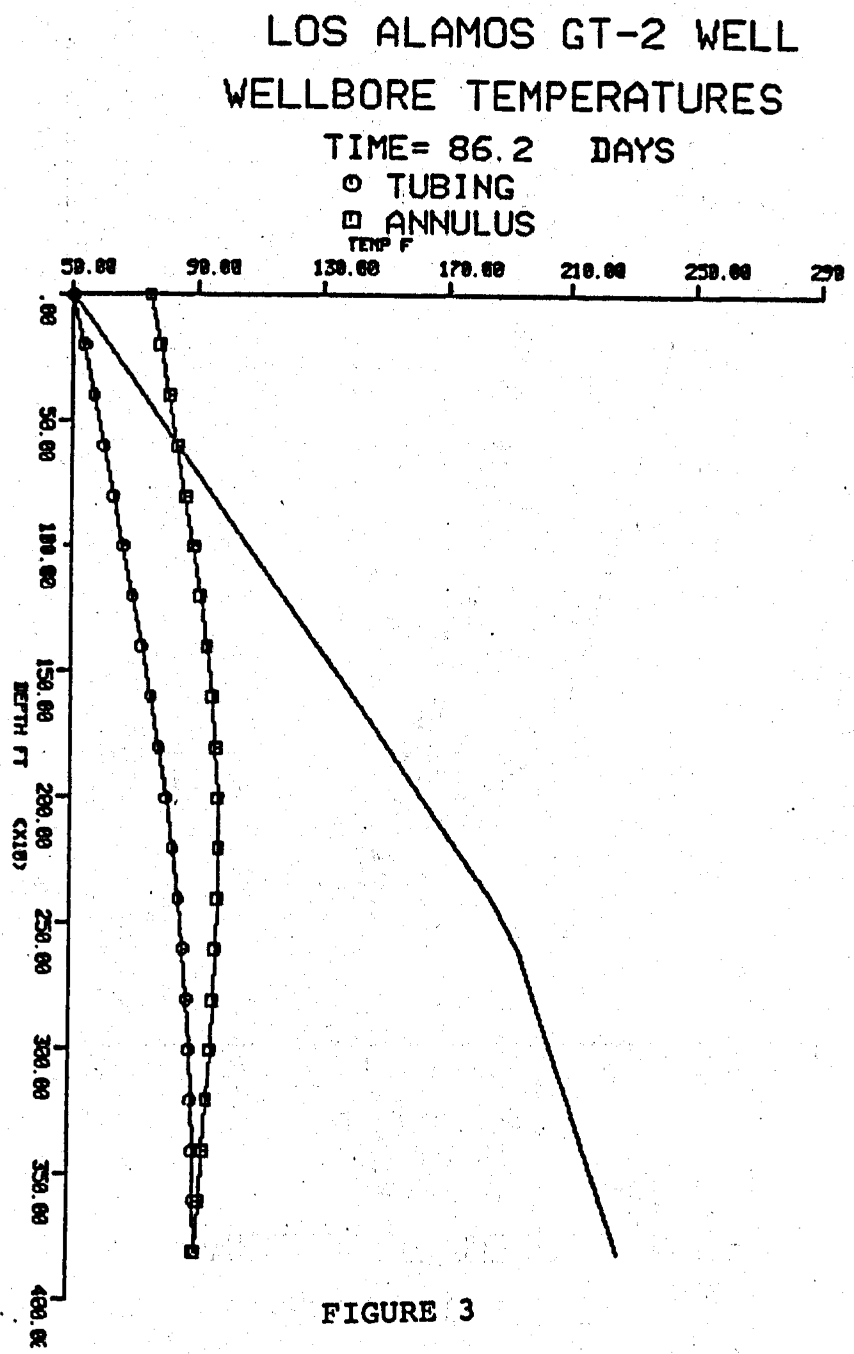

FIGURE 3

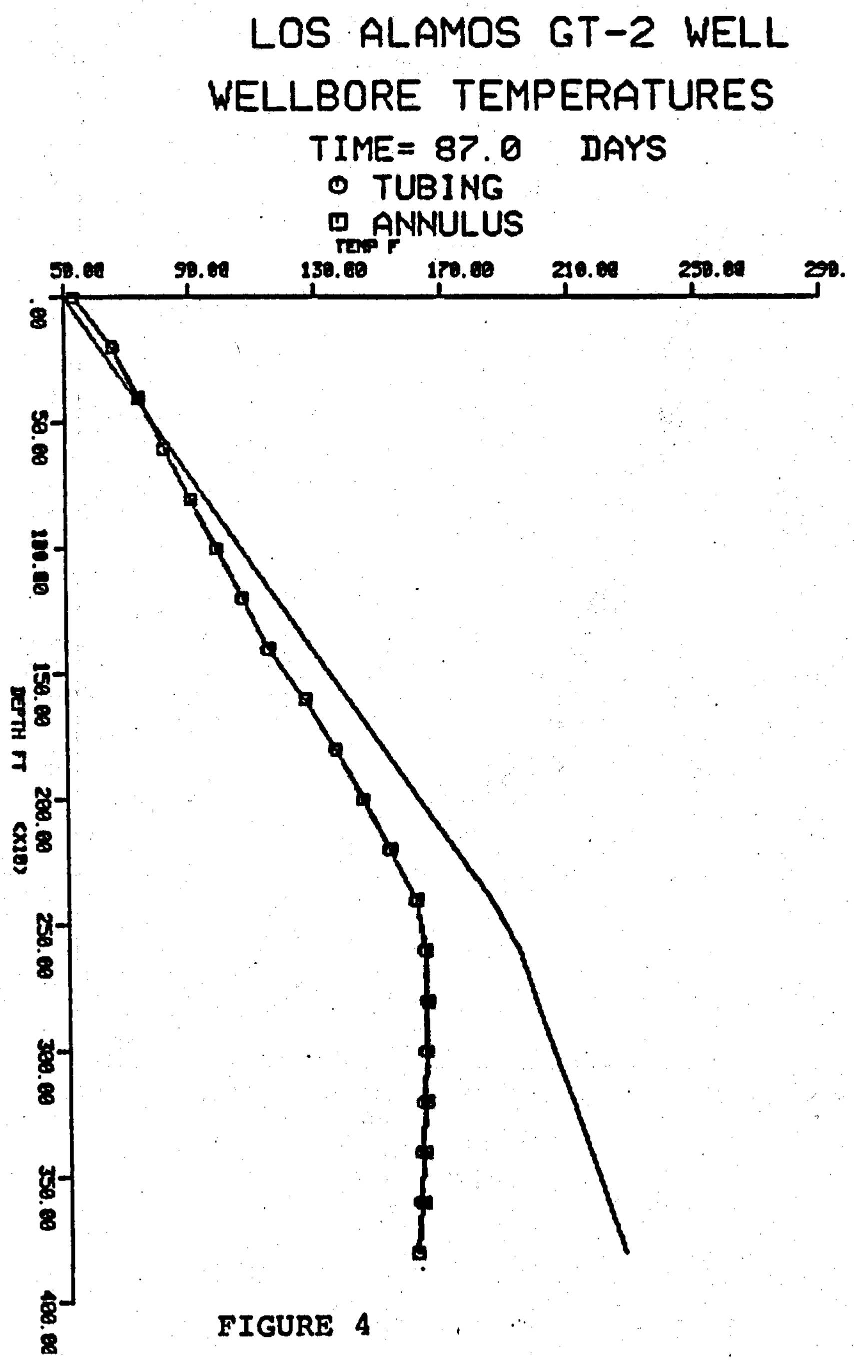

FIGURE 4

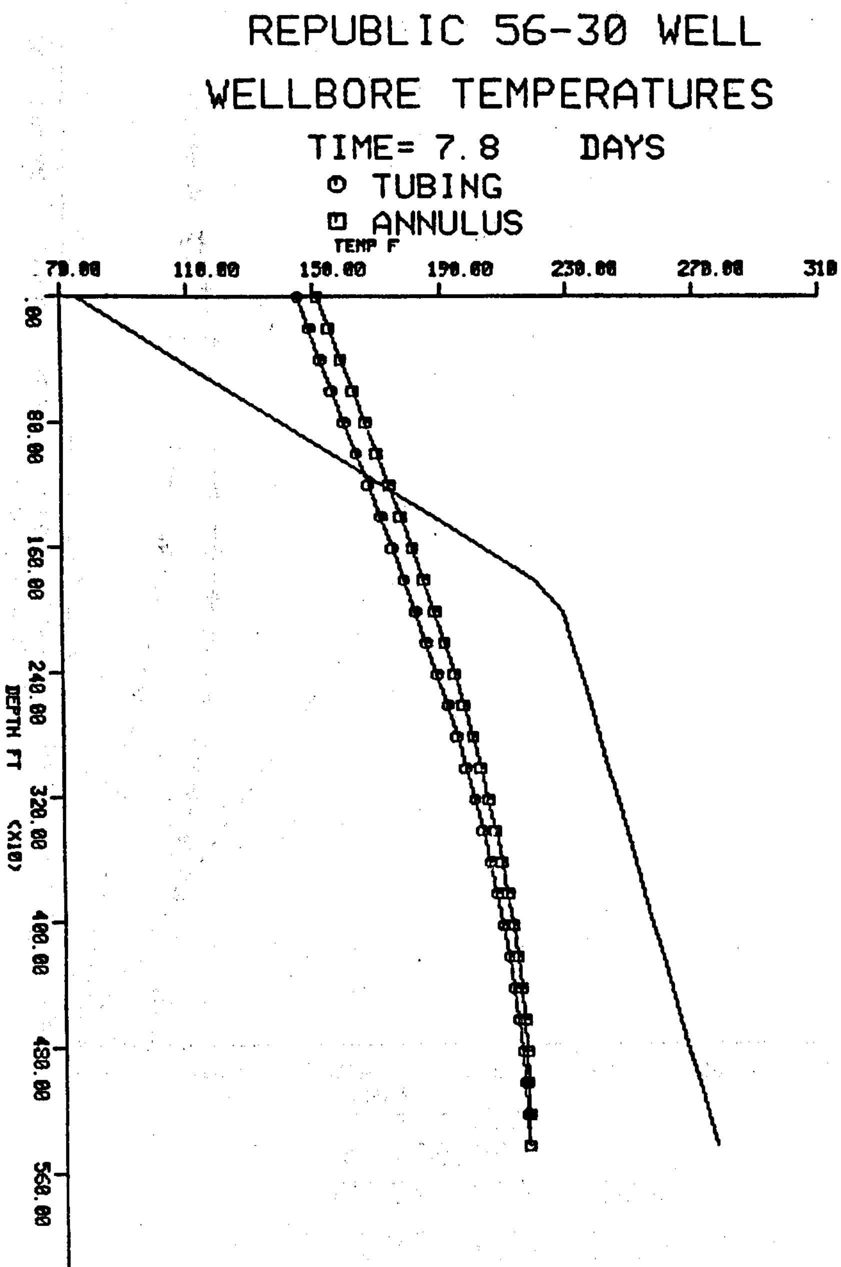

FIGURE 5

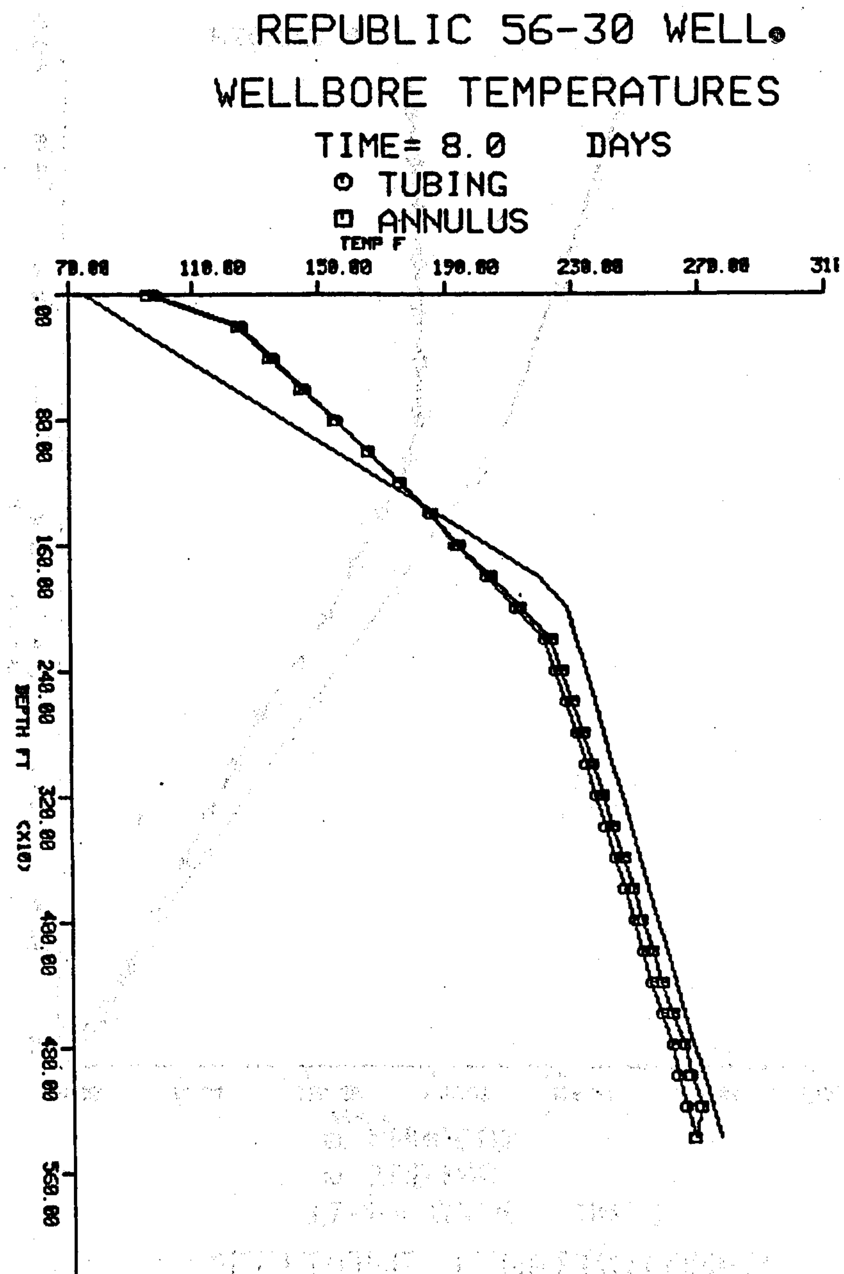

FIGURE 6

LOS ALAMOS GT-2 WELL

BIT TEMPERATURE

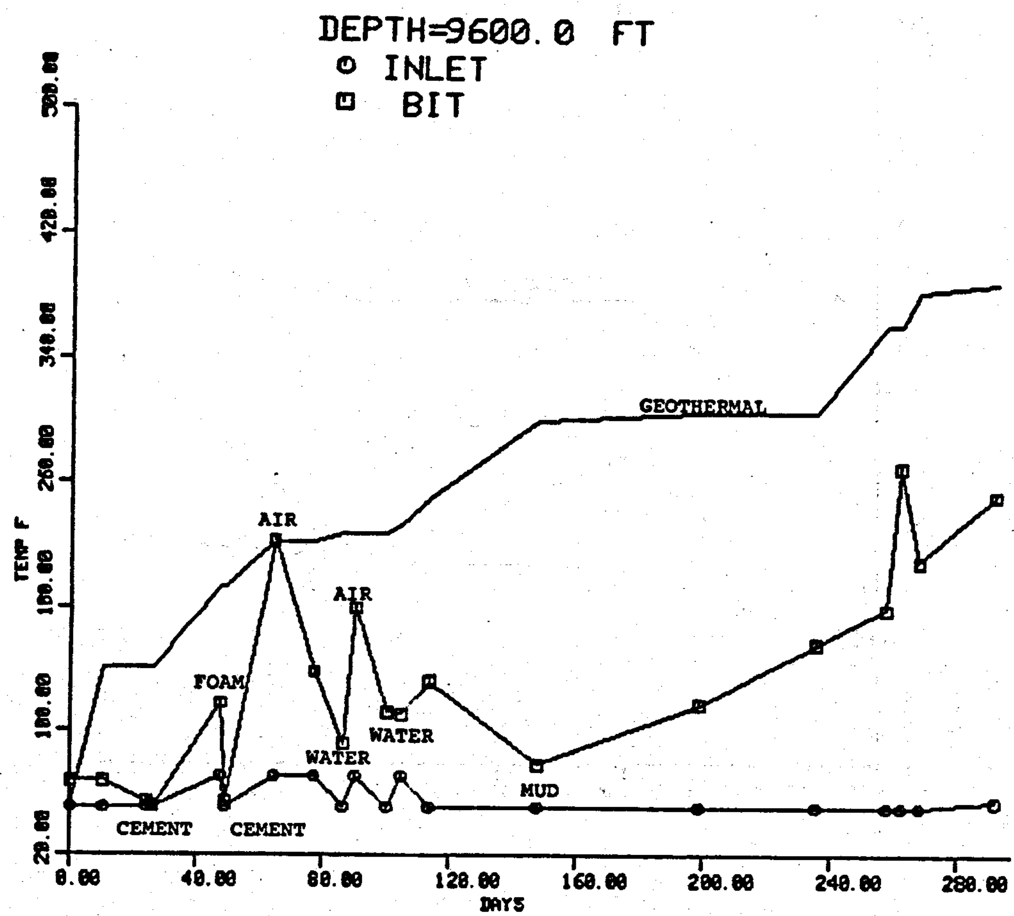

FIGURE 7

REPUBLIC 56-30 WELL

BIT TEMPERATURE

DEPTH=7600.0 FT

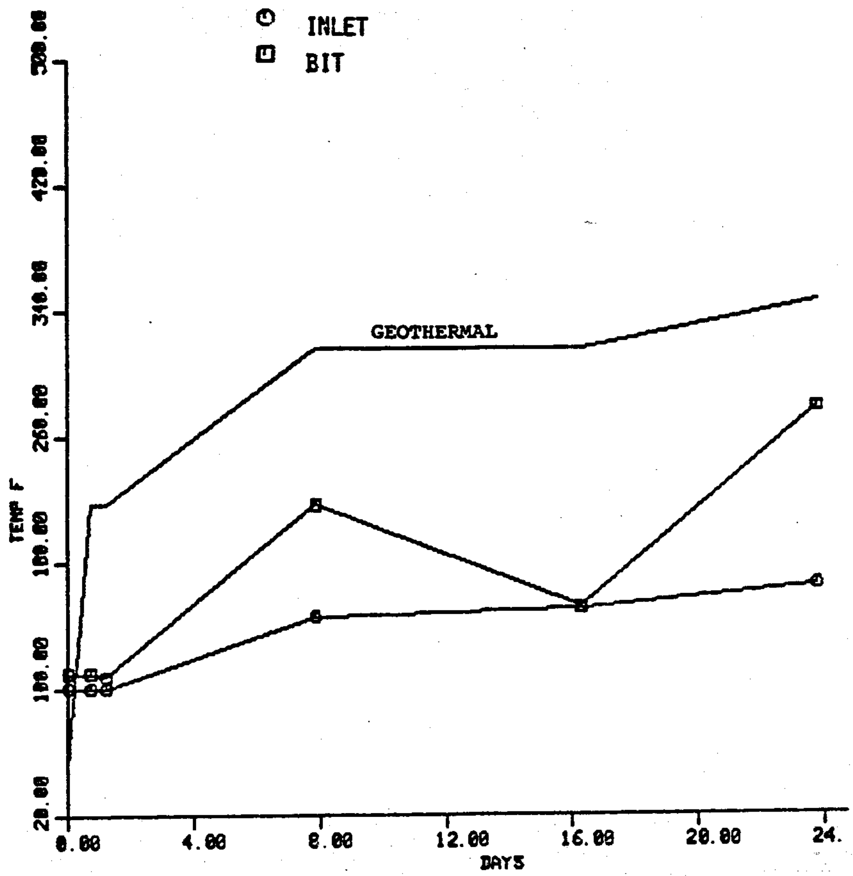

FIGURE 8

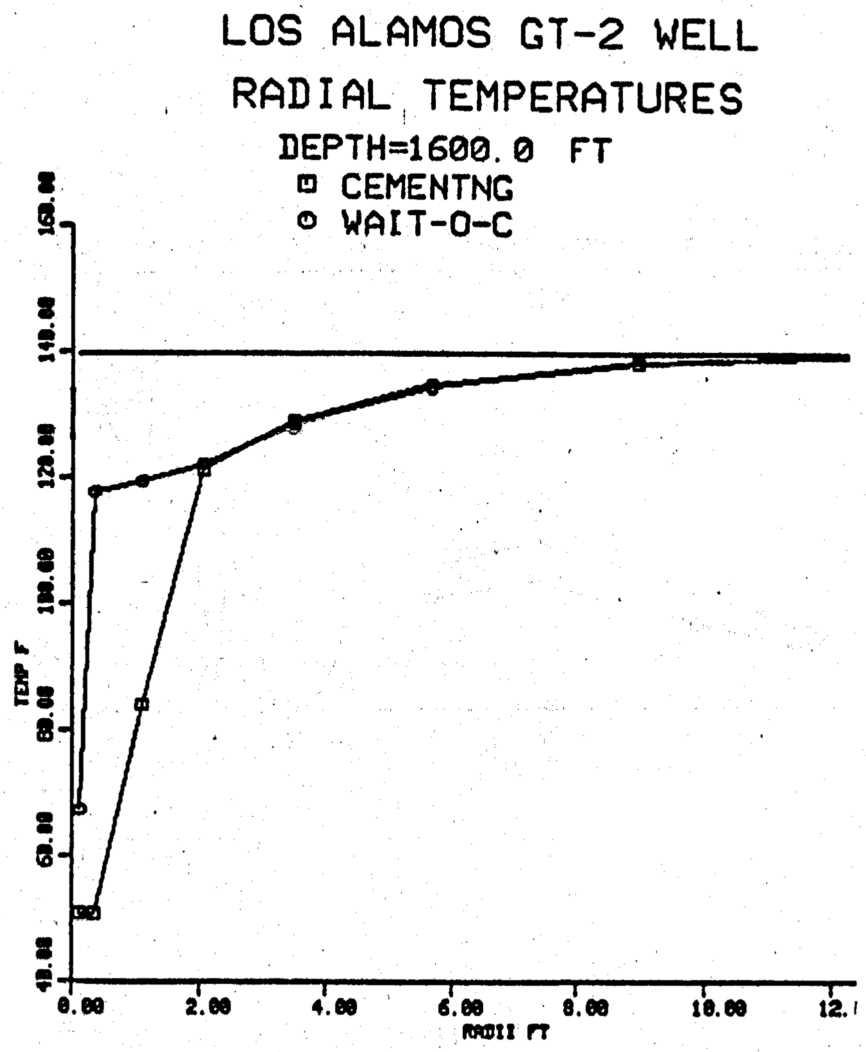

FIGURE 9

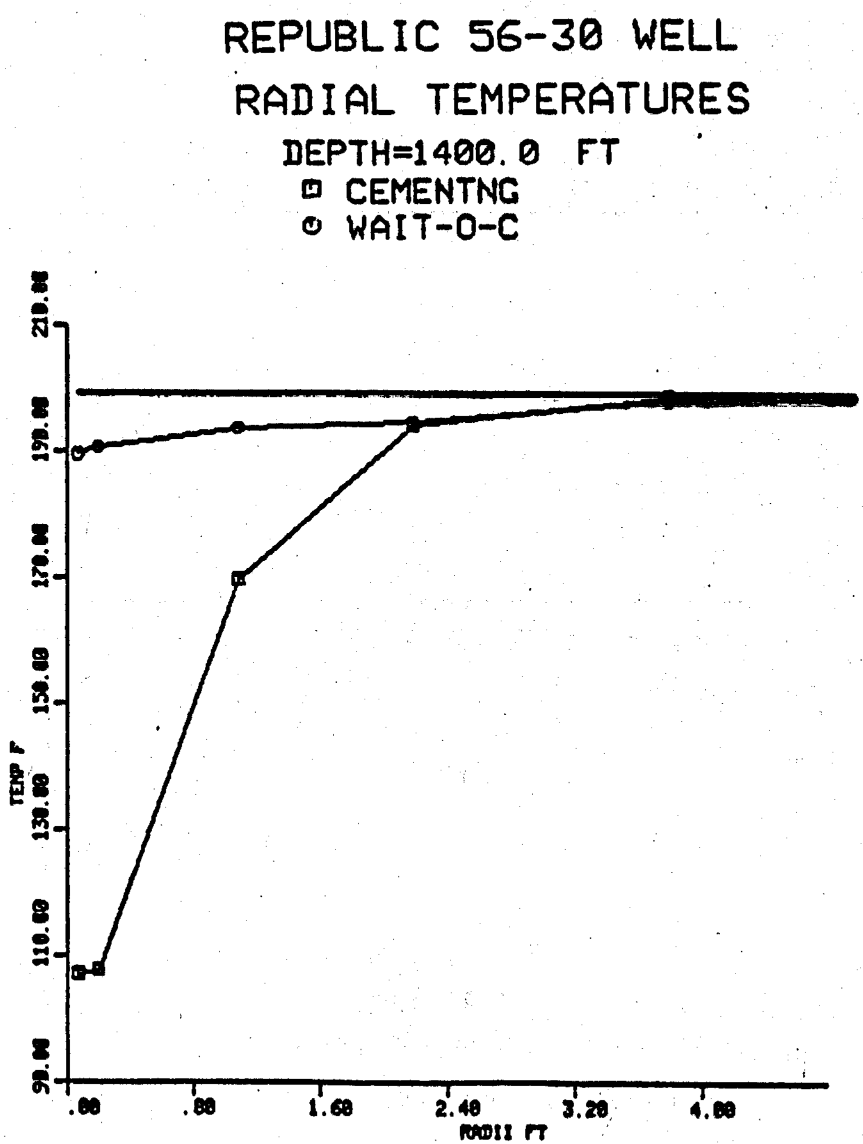

FIGURE 10

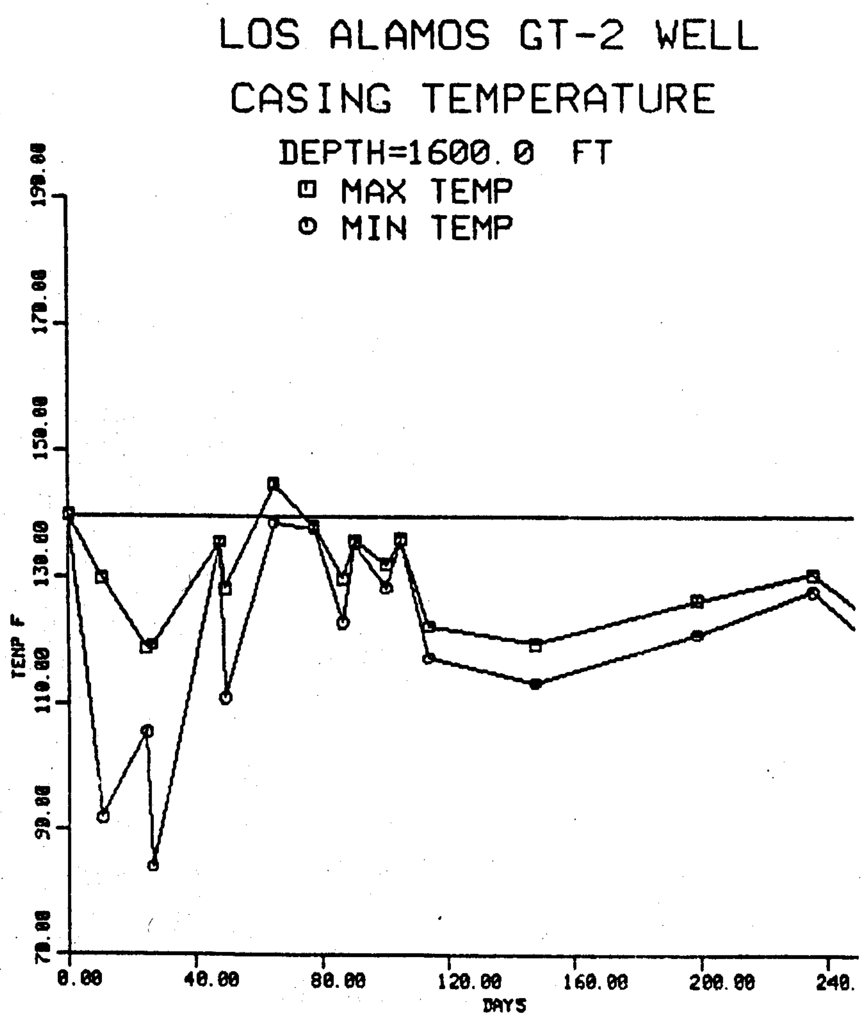

FIGURE 11

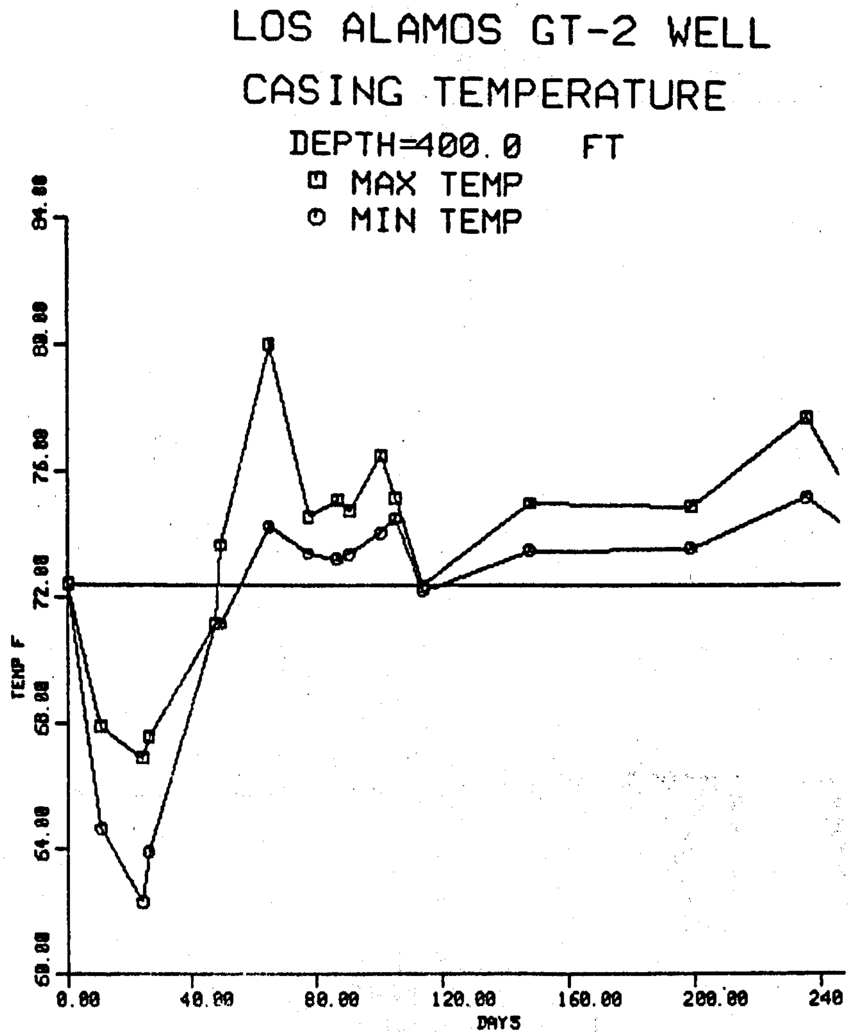

FIGURE 12

REPUBLIC 56-30 WELL

CASING TEMPERATURE

DEPTH=1400.0 FT

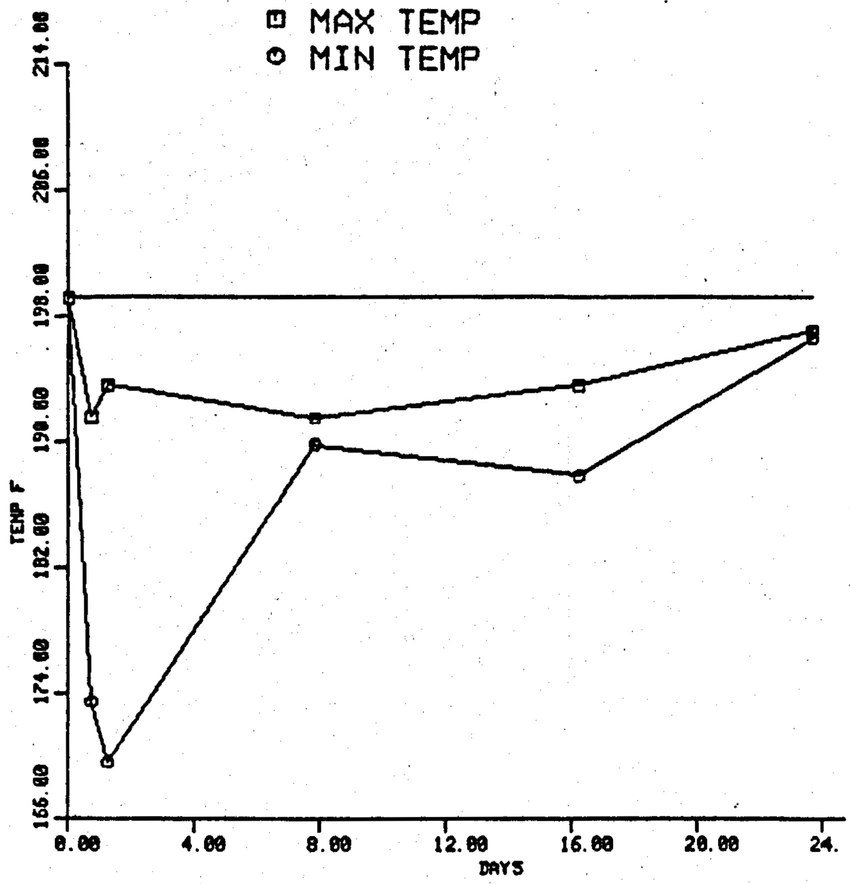

FIGURE 13

REPUBLIC 56-30 WELL

CASING TEMPERATURE

DEPTH=400.0 FT

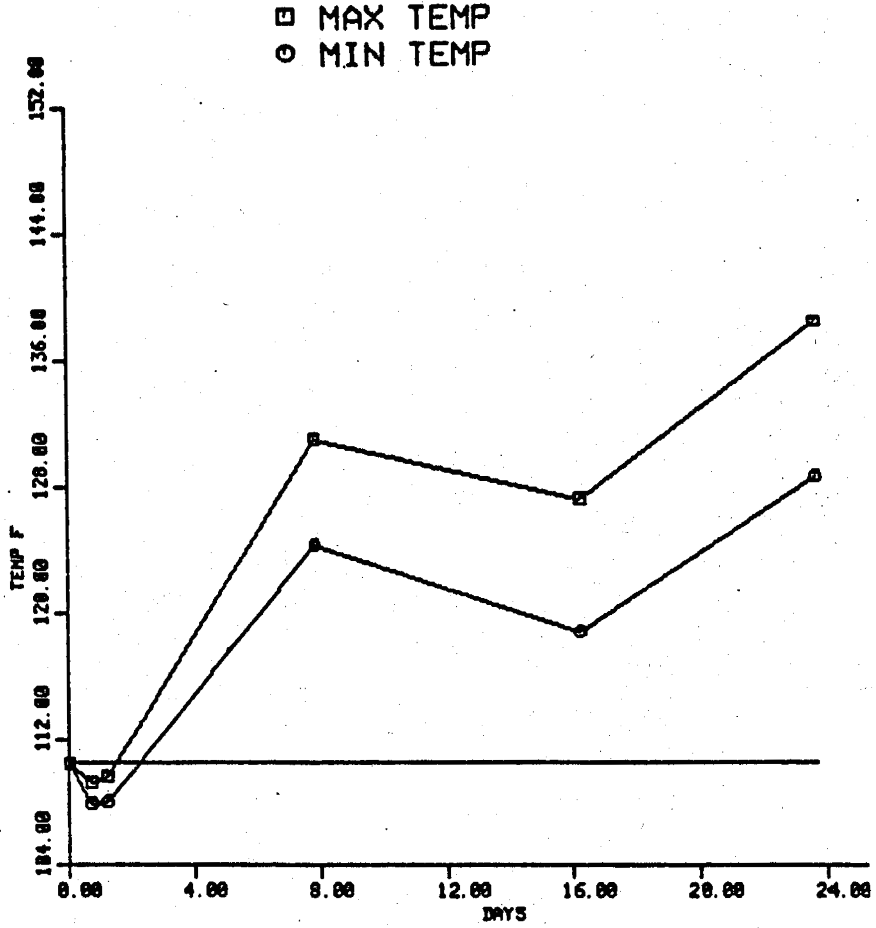

FIGURE 14